ANSWERS TO REVIEWER #2

The manuscript addresses the impact of climate change on water resources in Northeast Brazil, a region with significant water scarcity. It integrates a mix of methodologies, including climate modeling using RCP scenarios, remote sensing, and on-site measurements, to analyze evaporation dynamics. This comprehensive approach offers valuable insights for water resource management in the region. However, several concerns need addressing, as outlined below.

We are grateful for the reviewer's comments, which are extremely constructive. Indeed, we agree that many aspects need to be better outlined and that the suggested adjustments will add clarity to our approach and methods.

The reviewer's comments are in **black** and our answers in **blue**.

Major Comments

1. Uncertainties in Measurement and Modeling

1.1 Distance of Meteorological Station (Lines 360-365):

Considering the cited literature suggesting significant overestimation of open-water evaporation from distant measurements, the use of data from a weather station 20 km away from the reservoirs to correct bias and calculate evaporation is problematic and compromises the overall argument on data accuracy.

Response: The meteorological variables did not present discrepancies that significantly alter the estimate of the open-water evaporation rate in stations located in areas with similar and relatively close climatic conditions as in this study (15 km apart). For this response document, we selected 103 measurement days (covering 01/Aug to 01/Dec 2020) and analysed them: The INMET station recorded an average of 6.69 mm/day and stdv of 0.65 mm, and the station mounted on a raft on the reservoir recorded 6.39 mm/day and stdv of 0.75. The difference in accumulated evaporation between the two was 30.0 mm; overall the difference was 4.4%. We believe it is worth highlighting that there are in the State of Ceará (area of 149,000 km²) only 11 climatological stations with long data series (the information is found here, also in English version: https://www.agritempo.gov.br/agritempo/jsp/Estacao/index.jsp?siglaUF=CE&lang=pt_br).

1.2 Limitations of Remote Sensing Tools (Lines 179-182):

The use of only 24 satellite scenes over a 24-year period (1994-2018), comprising 18 from Landsat 5 and 6 from Landsat 8, presents a significant limitation for the study's objective of assessing reservoir evaporation trends in the stated region.

Response: More scenes were not available and even the available ones are suffering from some cloud coverage. Interestingly, MODIS/MERIS (DAILY acquisition) did not provide very much better coverage. Clearly, cloud cover is an issue in the area. Besides, even with daily acquisition satellites, we faced problems with spatial resolution, even after sharpening the images (see figure). We believe (and would like to know the reviewer's opinion) that obtaining more recent Landsat 8 images (at least two per year, from 2019 to 2023) would add another five years to the series, making it broader and more representative.

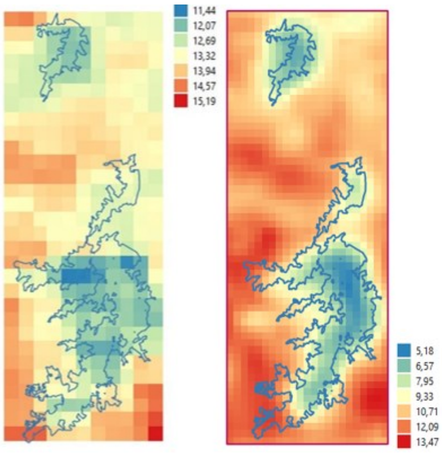

Fig 1: On the left, MODIS image with 1km pixels, on the right with 500m resolution.

We have tried also to use the MOD16 product, which provides 500 x 500 m land surface ET datasets for vegetated land areas at 8-day, monthly and annual intervals. The algorithm uses the Penman-Monteith approach to calculate plant and canopy transpiration, as well as soil evaporation (Dias et al., 2021). The pixel values for the two Evapotranspiration layers (ET and PET) are the sum of all eight days within the composite period. We tried to compare AquaSEBS with the PET product,but it was not possible to obtain MODIS scenes on consecutive days due to cloudiness.

Averaging just one scene per year, this frequency (added with consistency issues between the different Landsat products) is arguably insufficient for capturing the complex and dynamic nature of evaporation processes, which are subject to seasonal fluctuations and other meteorological variations. The limitations in using satellite imagery during the rainy season due to cloudiness and their implications on temporal resolution and accuracy of evaporation measurements are acknowledged but not thoroughly analysed.

Response: That is true. However, with regard to the very few available point stations that currently "capture" the temporal variability of evaporation, we think that the remote sensing product adds an interesting perspective on the spatial variability that is clearly evident but invisible to the point stations. Ideally, the approaches should be combined in a way.

The manuscript should address how these limitations impact the overall conclusions. Additionally, employing cloud-penetrating radar or microwave remote sensing (e.g. Synthetic Aperture Radar (SAR)) could have mitigated this limitation.

Response: Interesting approach to think of SAR data. Radar is not affected by clouds and can substitute or replace optical data in many respects but not thermal data that are required for evaporation assessment. We are not aware of a remote sensing algorithm to assess evaporation based on RADAR but would be most interested to learn if we missed a contribution on the topic.

We are aware of two investigations on this topic: one which estimates evaporation of groundwater (Wadge and Archer, 2003), and other investigates soil surface moisture estimation using ENVISAT ASAR radar data for soil evaporation evaluation (Zribi et al, 2011).

SAR is not typically used to directly measure evaporation from open water surfaces due to its operating frequency and the physical properties of water. SAR primarily detects microwave radiation, which interacts differently with different types of surfaces. Evaporation from open water surfaces involves the process of liquid water transitioning into water vapor due to heat energy from the environment. SAR is not sensitive to this process directly because water in its liquid state has relatively low emissivity and does not scatter microwave radiation significantly.

While SAR itself may not directly measure evaporation rates, it can contribute valuable information to studies investigating for example: water body dynamics (SAR can monitor changes in water extent, water level, and water movement over time. Understanding these dynamics can help estimate water loss through evaporation, especially when combined with other data sources such as meteorological data); and calibration and validation: SAR data can be used in conjunction with other remote sensing data (e.g., optical imagery, thermal infrared imagery) and in situ measurements to calibrate and validate evaporation models and estimates derived from other sensors.

Integrating SAR data with other datasets and models could indeed improve our understanding of this complex process. With regard to limitations and conclusions, there will likely never be a purely EO-based assessment of evaporation in this area of the world. However, we think that EO could support “traditional” evaporation point measurements, which currently occur in Ceará with class A pan measurements, water balance or equations based on measurements from meteorological stations. These methods require different parameterizations. The difficulty in characterizing these parameters makes such approaches complex to use under operational conditions, or in regions with limited ground-truth measurements.

1.3 The manuscript's approach of comparing point data from a single meteorological station with pixel data from remote sensing poses significant challenges that are not adequately addressed.

Point data is highly localized and may not represent wider regional conditions, while pixel data offers a broader, albeit less detailed, view. Without proper integration and analysis methodologies, this disparity can lead to misinterpretations or oversights in understanding regional phenomena like evaporation.

The manuscript's lack of discussion on how it reconciles these two data types is a notable omission.

Response: We used a floating raft with an on-board meteorological station to compare with the calculations made by the AquaSEBS algorithm. When writing this answer, we decided to compare the KR (0.73) with the real AquaSEBS measurements. We must draw attention to the lower values, which were obtained on cloudy days, which may have interfered with the quality of the image. It can be seen that the values are not so disparate.

Here, we have selected a few acquisitions to compare and present to the reviewer. Perhaps, presenting the data in this way in the finalised and revised document could be more useful and informative to the readers.

Table 1: Comparison between AquaSEBS acquisitions and hypothetical evaporation using KR = 0.73. All values are in mm day $^{-1}$

Date	**On-land**	**On-water/raft**	**AquaSEBS**	**E_{land}/E_{water}**	**Hypothetical AquaSEBS (E_{land} *KR)**
22 out 2019	7.60	6.37	4.50	0.84	5.55
18 jun 2020	7.57	6.27	4.50	0.83	5.53
23 jul 2021	7.55	7.62	7.92	1.01	5.51
Average	7.57	6.75	5.64	0.89	5.53
Stdev	0.03	0.75	1.97	0.10	0.02

We would like to highlight that these data are the best we have for the region, and surely remote sensing tools and efforts like this investigation can provide valuable information for improving evaporation estimates, especially in regions with limited meteorological data coverage. Satellite-based observations can provide information on water surface area, water level fluctuations, and changes in water temperature, aiding in the estimation of evaporation from open water surfaces. Remote sensing data can also be integrated with hydrological models, land surface models, and evapotranspiration models to improve spatially distributed evaporation estimates. Assimilating remote sensing observations into model simulations can enhance the accuracy and spatial resolution of evaporation estimates, especially in regions with heterogeneous landscapes and limited ground-based observations. Remote sensing-derived evaporation estimates can be validated and calibrated using ground-based measurements from meteorological stations. Comparing remote sensing-derived estimates with in-situ measurements allows for the evaluation of model performance and the identification of uncertainties. A less mentioned but important issue is data accessibility and cost-effectiveness: Remote sensing data are increasingly accessible through open-access platforms, making them a cost-effective solution for obtaining spatially distributed evaporation information in data-scarce regions, such as the Brazilian semiarid. Even though our measurements are not ideal, we believe that by leveraging remote sensing tools and integrating satellite observations with traditional meteorological data sources, researchers can enhance spatially distributed evaporation estimates, providing valuable insights for water resource management, climate studies, and environmental monitoring in regions with limited meteorological data coverage.

2. Climate Model Uncertainties and Bias Correction (Section 5.1, Lines 390-405):

2.1 Given the high variability between regional model outputs and the historical series for each model which indicates considerable uncertainties (as described in the manuscript) the manuscript's use of the Linear Scaling Method (LSM) for bias correction of climate model outputs presents notable limitations.

LSM's simplistic approach assumes stationarity and may inadequately represent extreme weather events and the intricate interactions between various climatic factors. The effectiveness and limitations of the bias correction methods used need a more critical examination.

Response: The reviewer's point is valid, LSM is a straightforward and commonly used approach for bias correction in hydrology and climatology studies, however it is often used in studies of hydrological impacts of climate change (to name some Althoff et al., 2020; Oliveira et al., 2017; Fiseha et al., 2014). For the purposes of this study, as well as those mentioned above, the method is sufficiently satisfactory in hydrology. Moreover, its usefulness in data-poor environments is remarkable. In regions with limited observational data or where alternative bias correction methods may be impractical, the LSM can provide reasonable corrections that improve the reliability of climate model outputs or observational analyses (Maraun et al., 2018). While the LSM may not fully capture the complexities of biases in climatic data and may not always yield optimal corrections, its benefits in terms of simplicity, transparency, and versatility make it a valuable tool for bias correction in various climate studies and applications.

In any case, for the final version, we can present as supplementary material a comparison of our results with the more sophisticated Quantile-Mapping method (Teutschbein and Seibert, 2012).

3. Evaporation Analysis and Water Availability (Sections 5.2 and 5.3, Lines 430-470):

3.1 Opposing Trends in Evaporation - The observation of two opposite trends of evaporation estimates in the study area based on different models is significant. However, the manuscript lacks a detailed analysis of the potential reasons behind these divergent trends, and nor did it present more model ensembles to weigh on a more plausible direction.

Response: We agree with the reviewer that an ensemble would be more appropriate for such a divergent result. In fact, in one of the phases of the study, we ran an ensemble of the models and found, albeit less significantly, an upward trend was observed (+3% in the dry season, compared to +6% in the worst-case scenario). The results will be in the revised paper. Indeed, it is common practice in climate research to compare and evaluate multiple models and ensembles to identify commonalities and uncertainties in simulated climate responses. Moreover, we will include the following text in section "5.1 Uncertainties addressed in measurement and modelling":

"CanESM2 (Chylek et al., 2011) and MIROC5 (Watanabe et al., 2010) have some differences in their model configurations, parameterizations, and simulation outputs, namely: i) Model Physics and Dynamics: CanESM2 and MIROC5 use different atmospheric and oceanic dynamical cores, which can lead to differences in the representation of atmospheric and oceanic processes. For example, differences in how convection, cloud formation, and ocean circulation are parameterized can influence simulated climate patterns and variability; ii) Forcing Scenarios: CanESM2 and MIROC5 may be driven by different historical and future greenhouse gas emissions scenarios and external forcings. Variations in the scenarios used to force the models can lead to differences in simulated climate responses, particularly for future projections of temperature, precipitation, and other climate variables; iii) Model Calibration: Each model undergoes a process of calibration and tuning to ensure that its simulations are consistent with observed climate variability and change. The specific calibration and tuning procedures used for CANESM2 and MIROC5 may differ, leading to differences in model behaviour and performance; iv) Data Assimilation and Initialization: Differences in how observational data are assimilated into the models and how initial conditions are initialized can

also lead to divergent simulation outcomes. Variations in data assimilation techniques and initialization procedures can affect the skill and reliability of model simulations.
These differences between CanESM2 and MIROC5 can contribute to divergent climate projections, particularly at regional scales and for specific study areas. Understanding these distinctions is important for interpreting and contextualizing model results and for assessing the robustness of climate change projections."

3.2 The Penman method may not fully capture the complex evaporation dynamics in a tropical region. The paper should compare its performance with other methods, like Penman-Monteith, in this specific climatic context, or at least discuss its appropriateness.
Response: Indeed, one of the main limitations of the original Penman (1948) equation is its simplifying assumptions and empirical coefficients, which may not fully capture the complexities of evaporation processes in tropical climates. For example, the Penman equation assumes constant conditions over a 24-hour period, neglects the effects of diurnal variations in temperature, humidity, and radiation, and may not adequately account for the specific atmospheric and surface characteristics of tropical regions. However, has undergone adaptations (Valiantzas 2013) and in this work we strictly follow the steps described by Allen et al. (1998) and McMahon et al. (2013). Studies such as those by Donohue et al. (2010) and Elsawwaf et al. (2010) report that Penman (1948) produces the most realistic estimates of evaporation and is the most comparable to energy balance estimates using the Bowen ratio. In a recent study, Rodrigues et al. (2023) demonstrated to what extent two direct-measurement sensors and two physically-based models (Penman and modified Dalton) accurately estimate the evaporation of a tropical reservoir (same study region of the present paper). The Penman (1948) model, based on data from a floating station, showed good results ($r > 0.7$) for the 12 h time step or daily evaporation, comparing with the direct measurements.

Minor Comments

Future Research Directions (Section 6, Lines 510-515):

The manuscript highlights the need for an integrated approach but does not provide a clear roadmap for integrating physical climate impacts with societal demands and water use analysis (e.g. RCP-SSP scenarios instead of just RCPs).
Response: We believe this is extremely important, but it is outside the scope of this research. Nevertheless, we will insert the following text into the discussion section of the revised paper:

"To achieve an integrated approach for integrating physical climate impacts with societal demands and water use it is first necessary to understand the local context and the specific needs of each region, economic sectors and water resource managers. Then, a comprehensive assessment of the projected impacts of climate change on regional water resources, considering extreme weather events and changes in hydrological regimes. An accurate assessment of the current and future availability of water resources is essential, taking into account surface and groundwater, water quality and its demand. Hydrological models and reliable field data to quantify water availability under different climate scenarios are essential.
Identifying social demands and vulnerabilities is crucial, so the main social demands for water should be identified, including agricultural, industrial, urban, ecological, and recreational use,

etc. Analysing social vulnerabilities related to water availability, considering factors such as poverty, social inequality, access to water resources and resilience to climate change. Vulnerable populations, marginalised groups, and areas prone to adverse impacts from water scarcity need to be identified.
It is necessary to actively involve local stakeholders, including communities, community leaders, non-governmental organisations, the private sector and government authorities, at all stages of the analysis and planning process. Promote inclusive participation, interdisciplinary dialogue and consensus building around adaptation and water management strategies.
Finally, there must be constant monitoring and evaluation systems to follow up on the implementation of adaptation strategies and assess their impacts on water availability and welfare. We recommend the work of Sivapalan et al (2012) as a starting point on that matter: "Socio-hydrology: a new science of people and water"."

Certain parameters in the Penman equation, such as the psychrometric coefficient and latent heat of vaporization, are assumed constants. It's important to justify these assumptions or discuss their potential impact on the results.
Response: We are grateful to the reviewer for the observation and note that this is a textual error. The following text will be inserted in Section 3.2.1 of the paper:

"γ is the psychrometric coefficient; ρ is the density of water (1000 kg m^{-3}); λv is the latent heat of vaporization The procedure to obtain γ and λ is described in Annex 2 of the Food and Agriculture Organization of the United Nations (FAO) 56 protocol (Allen et al. 1998)."

The calibration of the KR coefficient using AquaSEBS and Penman Equation is mentioned, but details on the validation process, error metrics, or comparison with ground-truth data are not provided.
Response: No calibration was done but a direct comparison of the methods using different approaches (EO and Penman applied to a nearby climatological station). Our intention was to use an index that would correlate measurements in different environments. Of course, the mean of 0.73 and the median of 0.74 seemed reasonable (for example, Mamede et al. (2012) indicates that the rate of evaporation in a semi-arid reservoir is approximately 0.70 times the evaporation of a class A pan). However, we know that depending on the size of the historical series, this value can also change. We would like to know if there are any suggestions for improvement from the reviewers on this aspect.

Cited literature, in alphabetic order:

Donohue et al. (2010) https://doi.org/10.1016/j.jhydrol.2010.03.020

Elsawwaf et al. (2010) https://doi.org/10.1016/j.jhydrol.2010.10.002

Mamede et al. (2012) www.pnas.org/cgi/doi/10.1073/pnas.1200398109

Marqaun et al. (2018) https://doi.org/10.1038/nclimate3418

Sivapalan et al (2012) https://doi.org/10.1002/hyp.8426

Wadge and Archer (2003) https://doi.org/10.1109/TGRS.2003.813747

Zribi et al (2011) https://doi.org/10.5194/hess-15-345-2011